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Glazial-marine Sedimentierung an der kanadischen Polargrenze nördlich der Axel Heiberg-lnsel

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Résumé de l'article

L'étude des carottes de sédiments recueillies à des profondeurs de 140 à 300 m sur la plate-forme de l'île Axel-Heiberg (82° N) renseigne sur la mise en place des sédiments sous une glace de mer pérenne. Elle révèle cinq faciès sédimen-taires: (A) boue sablo-caillouteuse avec structures de cailloux de délestage; (B) boues silteuses bioturbées; (C) lamines en mèches d'argile et d'argile silteuse; (D) sables et silts laminés et boue; (E) boue sablo-caillouteuse compacte. Les carottes renferment aussi des sédiments du substratum du Groupe de Eureka Sound du Paléogène et un dépôt tertiaire plus jeune, probablement de la Formation de Beaufort. Les âges se répartissent entre 1530 ± 60 BP (fades A) à 9950 ± 80 BP (fades D). Les taux de sédimentation varient selon les fades: ~ 0,8 cm ka-1 (fades B)14 cm ka-1 (faciès A), 90 cm ka_1 (faciès C), 134 cm ka_1 (faciès D). Le processus de sédimentation, interprété à partir de la sédimentologie, la palynologie et les foraminifères, comprend des intervalles durant lesquels la couverture de glace était continue avec apport réduit de débris grossiers alternant avec des périodes de mer dégagée avec apport sédimentaire élevé à partir des eaux de fonte ou des icebergs. Dans les carottes, le substratum du Néogène n'est recouvert que de sédiments marins. L'absence de diamicton laisse présumer que la glace continentale n'a jamais occupé cette partie de la plate-forme. L'interprétation qu'on fait du processus de sédimentation correspond de façon générale aux données tirées de l'île d'Ellesmere, mais diffère beaucoup des études sur le milieu marin de latitudes plus méridionales.

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GLACIAL-MARINE SEDIMENTATION, CANADIAN POLAR MARGIN, NORTH OF AXEL HEIBERG ISLAND*

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ABSTRACT Sediment cores, taken at depths of 140 to 300 m across the northwestern shelf of Axel Heiberg Island (82° N), record the deposition of sediments under perennial sea ice. Five sedimentary facies are recognized: (A) soft pebbly-sandy-mud with dropstone structures; (B) bioturbated silty muds; (C) wispy-laminated silty clay/clay; (D) laminated sands/silts and mud; (E) firm pebbly-sandy-mud with chaotic pebble fabrics. Other sediments include terrestrial bedrock of Paleogene Eureka Sound Group, and a younger Tertiary deposit, possibly the Beaufort Formation. Ages range from 1530 ± 60 BP (Facies A) to 9950 ± 80 BP (Facies D). Sedimentation rates vary as follows: ~ 0.8 cm ka^{-1}, Facies B; 4 cm ka^{-1}, Facies A; 90 cm ka^{-1}, Facies C; 134 cm ka^{-1}, Facies D. The sedimentation history, as interpreted from the sedimentology, palynology and foraminiferal results, suggests intervals of more continuous ice cover, with a reduced influx of coarse ice-rafted detritus, alternating with more open water conditions, and high sediment input from meltwater and/or floating icebergs. Only marine sediments overlie Neogene bedrock in the cores. The absence of diamictons at the core sites suggests that grounded ice perhaps never occupied this part of the Axel Heiberg Island shelf. The interpreted history of sedimentation generally corresponds to the land-based record from Ellesmere Island, but differs significantly from marine-based studies in more southern latitudes.

RÉSUMÉ *Sédimentation glaciomarine au nord de l'île Axel-Heiberg, à la marge polaire du Canada.* L'étude des carottes de sédiments recueillies à des profondeurs de 140 à 300 m sur la plate-forme de l'île Axel-Heiberg (82° N) renseigne sur la mise en place des sédiments sous une glace de mer pérenne. Elle révèle cinq faciès sédimentaires: (A) boue sablo-caillouteuse avec structures de cailloux de délestage; (B) boues silteuses bioturbées; (C) lamines en mèches d'argile et d'argile silteuse; (D) sables et silts laminés et boue; (E) boue sablo-caillouteuse compacte. Les carottes renferment aussi des sédiments du substratum du Groupe de Eureka Sound du Paléogène et un dépôt tertiaire plus jeune, probablement de la Formation de Beaufort. Les âges se répartissent entre 1530 ± 60 BP (faciès A) à 9950 ± 80 BP (faciès D). Les taux de sédimentation varient selon les faciès: ~ 0,8 cm ka^{-1} (faciès B), 4 cm ka^{-1} (faciès A), 90 cm ka^{-1} (faciès C), 134 cm ka^{-1} (faciès D). Le processus de sédimentation, interprété à partir de la sédimentologie, la palynologie et les foraminifères, comprend des intervalles durant lesquels la couverture de glace était continue avec apport réduit de débris grossiers alternant avec des périodes de mer dégagée avec apport sédimentaire élevé à partir des eaux de fonte ou des icebergs. Dans les carottes, le substratum du Néogène n'est recouvert que de sédiments marins. L'absence de diamicton laisse présumer que la glace continentale n'a jamais occupé cette partie de la plate-forme. L'interprétation qu'on fait du processus de sédimentation correspond de façon générale aux données tirées de l'île d'Ellesmere, mais diffère beaucoup des études sur le milieu marin de latitudes plus méridionales.

ZUSAMMENFASSUNG *Glazial-marine Sedimentierung an der kanadischen Polargrenze nördlich der Axel Heiberg-Insel.* Sedimentkerne, die in Tiefen von 140 bis 300 m quer durch den nordwestlichen Schelf der Axel Heiberg-Insel gewonnen wurden (82° N), bezeugen die Ablagerung von Sedimenten unter dem ganzjährigen Meereseis. Man kann fünf Sediment-Fazies erkennen: (A) weicher, kiesig-sandiger Schlamm mit Treibeisstrukturen; (B) Bioturbationstrukturen schlickiger Schlamm; (C) dünnblättriger schlickiger Ton und Ton; (D) blättriger Sand/Schlick und Schlamm; (E) kiesig-sandiger Schlamm mit chaotischer Kiesstruktur. Andere Sedimente enthalten Erdfels der paläogenen Eureka-Sound-Gruppe sowie eine jüngere tertiäre Ablagerung, möglicherweise von der Beaufort Formation. Die Alter liegen zwischen 1530 ± 60 v. u.Z. (A-Fazies) bis 9950 ± 80 v.u.Z. (D-Fazies). Die Sedimentierungsraten variieren folgendermaßen: 0,8 cm ka^{-1} B-fazies; 4 cm ka^{-1}, A-Fazies; 90 cm ka^{-1}, C-Fazies; 134 cm ka^{-1}, D-Fazies. Die Sedimentierungsgeschichte wie sie mittels Sedimentologie, Palynologie und den Foraminifera-Ergebnissen interpretiert wird, läßt an Intervalle einer mehr kontinuierlichen Eisdecke denken, mit einem verringerten Einströmen groben vom Eis beförderten Steine, alternierend mit Bedingungen mehr offenen Wassers und einem hohen Sedimentzutrag durch Schmelzwasser und/oder treibende Eisberge. Nur marine Sedimente überlagern den Fels aus dem Jungtertiär in den Kernen. Das Fehlen von Diamiktons an den Bohrplätzen legt nahe, daß Kontinentaleis vielleicht niemals diesen Teil des Schelfs der Axel-Heiberg-Insel bedeckte. Die so interpretierte Geschichte der Sedimentierung stimmt im allgemeinen mit dem landbezogenen Beleg von der Ellesmere-Insel überein, unterscheidet sich aber deutlich von den meeresbezogenen Studien in südlicheren Breiten.

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INTRODUCTION

Today, multi-year sea ice permanently occupies the continental margin of the Queen Elizabeth Islands (Fig. 1). This region of continuous ice cover grades southwards to a seasonal ice zone, with summer open water, on the continental margins of Alaska, Siberia and Svalbard (Fig. 1). In the deep basins of the western Arctic Ocean, many studies have been made of the sediments (Clark *et al.*, 1980; Clark and Hanson, 1983; Mudie and Blasco, 1985; Aksu and Mudie, 1985a). Sedimentological studies have also been made along the margin of the Arctic Ocean where it is accessible by ships in summer, *e.g.* Alaskan Shelf (Barnes and Reimnitz, 1974), Siberian margin (Naugler *et al.*, 1974), and the Barents Sea (Vorren *et al.*, 1983). Furthermore, short cores (< 1.5 m) have been studied from channels east and west of Ellef Ringnes Island (Horn, 1987) and from the inter-island channels west and south of the Queen Elizabeth Islands (MacLean *et al.*, in press).

The present study describes cores collected in 1985 and 1986 from the Canadian Ice Island as it drifted from Nansen Sound westward to the northwestern part of Axel Heiberg Shelf (Figs. 1 and 2). The area sampled on the shelf is about 100 km^2, with water depths of 100 to 300 m (Mudie *et al.*, 1985, 1986). This study area is among the coldest and driest parts of the Canadian arctic islands, with a mean annual air temperature of –19° C and a mean July temperature of about 1°C. The mean annual runoff is only 25 mm (Hare and Thomas, 1979). Spring thaw is therefore slow and open water leads rapidly refreeze in the absence of strong winds.

The sedimentary facies and mineralogy found in these cores is discussed in detail elsewhere (Hein *et al.*, 1990). This paper presents new radiocarbon dates on molluscs and foraminifera, which allow a detailed account of the paleoenvironmental history of this area. In addition, updated bathymetric maps allow the surficial sediments to be more accurately related to the shelf topography. A qualitative model

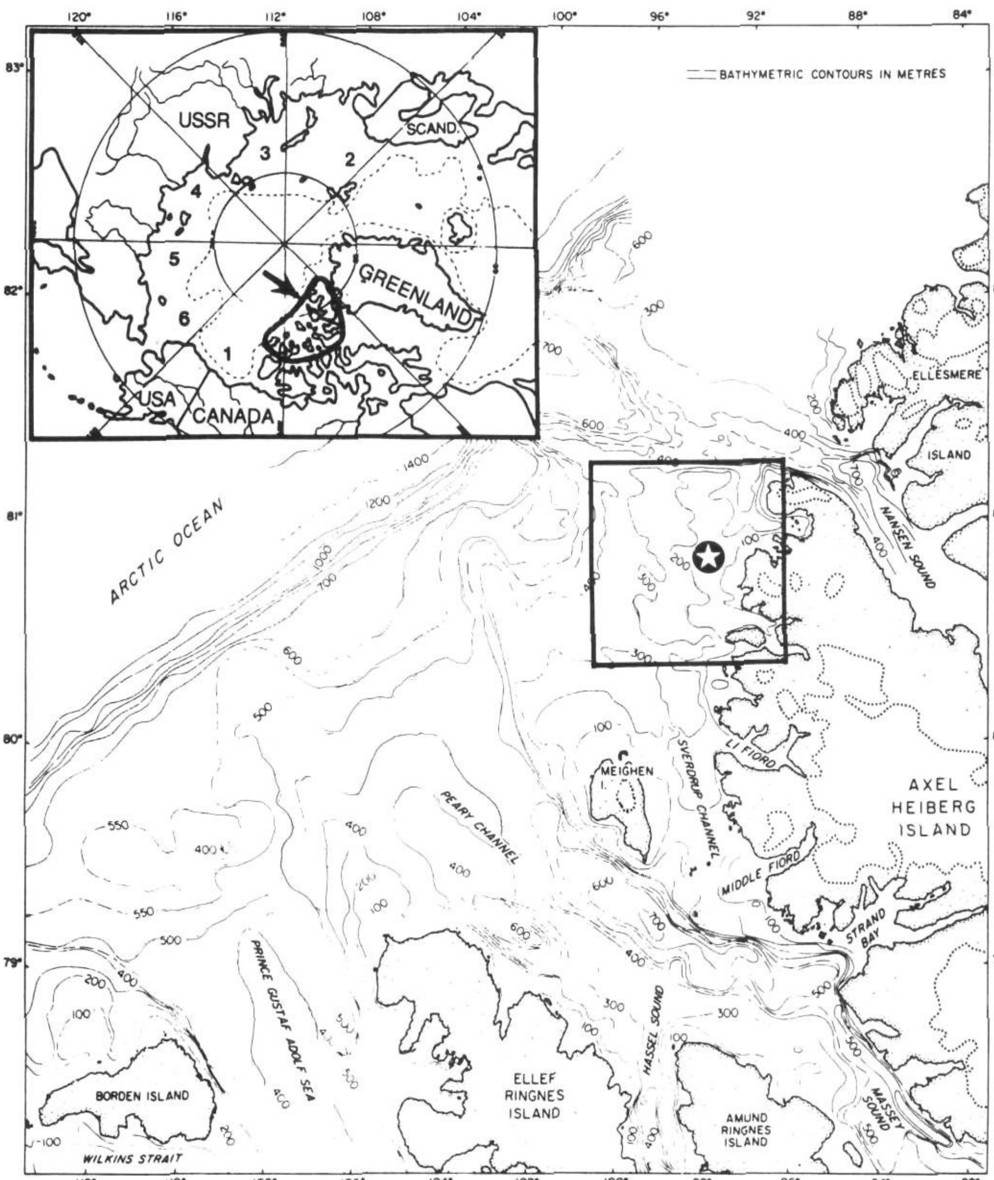

FIGURE 1. Map showing the bathymetry of the study area (marked *) in relation to the Arctic Ocean and Canadian Arctic islands, and indicating the possible maximum (heavy line) and minimum (hatched line) limits of the Wisconsinan continental ice in the Queen Elizabeth Islands (after Hodgson, 1989). Inset map shows the relation of the study area to other Arctic margins: 1) Alaskan shelf; 2) Barents shelf; 3) Kara shelf; 4) Laptev shelf; 5) Siberian shelf; 6) Chukchi shelf; dashed line = southern limit of perennial sea-ice cover.

*Carte bathymétrique de la région à l'étude (identifiée par *) en relation avec l'océan Arctique et les îles de l'Arctique canadien et illustrant les limites maximales (lignes pleines) et minimales (pointillé) probables des glaces continentales wisconsiniennes dans l'archipel de la Reine-Élisabeth (selon Hodgson, 1989). Le carton illustre la relation entre la région à l'étude et d'autres marges arctiques: 1) plate-forme de l'Alaska; 2) plate-forme de Barents; 3) plate-forme de Kara; 4) plate-forme de Laptev; 5) plate-forme de Sibérie; 6) plate-forme de Chukchi; tireté = limite septentrionale de la couverture pérenne de glace de mer.*

is presented for the textural and microfossil characteristics of the surficial sediments on this high arctic shelf. These sediments are relevant to the nature of high latitude paleoenvironmental change in the Queen Elizabeth Islands (Fig. 1) (Hodgson, 1985, 1989). Sedimentation processes in this perennially sea ice-covered margin may provide a useful analog for former glacial conditions further south.

GENERAL GEOLOGY AND BATHYMETRY

The bathymetry of the northwestern Axel Heiberg Shelf has recently been surveyed in detail (Mudie *et al.*, 1985; Mudie *et al.*, 1986) (Figs. 1 and 2) and confirms earlier interpretations that two submarine valleys, Nansen and Sverdrup Channels, dissect the shelf (Pelletier, 1966). The submarine valleys are separated by broad submarine banks which form the inner shelf above the 300 m isobath (Fig. 2). Locally, siliceous sponges and small molluscs are abundant on the shelf, forming reef mounds at water depths of about 90 to 125 m (Van Wagoner *et al.*, 1989).

The origin of this shelf morphology probably involved drowning and wave truncation of a Tertiary drainage system (Pelletier, 1966). The inter-island channels may be either Tertiary fluvial channels overdeepened by glaciation (Thorsteinsson and Tozer, 1968) or, alternatively, grabens or half-grabens associated with faulting during Miocene or Pliocene phases of the Eurekan rifting episode (England, 1987). The timing and extent of the last glaciation in the central Queen Elizabeth Islands is controversial (Dyke and Prest, 1987; Hodgson, 1989); however, most observations now reject the presence of a regional ice sheet (England, 1990).

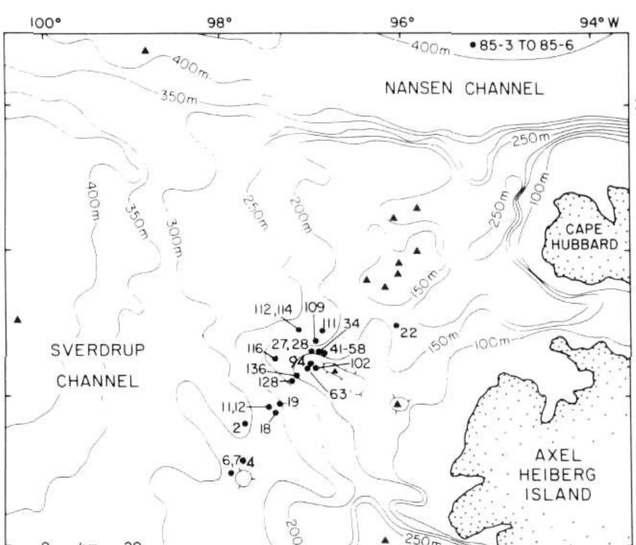

FIGURE 2. Location of cores (solid dots) and grab samples (triangles) in relation to detailed bathymetry of the central Axel Heiberg shelf. Cores 85-3 to 85-6 were taken in 1985; all other cores were collected in 1986.

Localisation des forages (points) et des échantillons de fonds marins (triangles) en relation avec la bathymétrie du centre de la plate-forme d'Axel Heiberg. Les forages n^{os} 85-3 à 85-6 datent de 1985: tous les autres ont été faits en 1986.

The Princess Margaret ice-cap presently covers Axel Heiberg Island above 2000 m (Fig. 1). Most glaciers terminate in broad valleys inland from the coast (Fortier *et al.*, 1963). Neogene and Quaternary deposits extend beyond the ice-caps and their associated landforms suggest a long interval of postglacial weathering (Fortier *et al.*, 1963). Blake (1970) proposed that the Queen Elizabeth Islands were occupied by the Innuitian Ice Sheet during the last glaciation; however, most data indicate the presence of only local ice caps which formed a noncontiguous cover termed the Franklinian Ice Complex (England, 1976; Hodgson, 1985). Ice retreat began by *9000 BP*.

Postglacial emergence on Axel Heiberg Island has not been studied in detail. A rebound curve for the Expedition area on western Axel Heiberg Island (Muller, 1963) shows rapid emergence. One shell date of 9000 ± 200 BP at 80 m above sea level provides a minimum estimate for emergence on the west coast (B. R. Pelletier, pers. comm., 1988). Raised beaches of less than 30 m above sea level on northern Axel Heiberg and Meighen islands are associated with a date of 8610 BP which suggests that emergence decreases towards the north. These data and studies of marine limits on northern Ellesmere Island (Bednarski, 1986; Evans, 1988; Lemmen, 1988) suggest that relative sea level on the Axel Heiberg Shelf may have been no lower than present during the last glaciation. In fact, given the emergence of Meighen Island (greater than 30 m above sea level), it is likely that much of the shelf was within the peripheral depression of the Axel Heiberg Island ice load during the last glaciation, hence sea level was likely *higher* than present during this interval (J. England, pers. comm., 1990). Thus, water depths for the central and inner shelf study area during the last glaciation were likely somewhat greater (perhaps 10-30 m) than today.

OCEANOGRAPHY AND ICE CONDITIONS

The physical oceanography of the Axel Heiberg shelf is similar to the water of the Canada Basin and inter-island channels (Melling *et al.*, 1964). In these areas, water is strongly stratified, with cold (–1.5° to –1.8° C), low salinity (29-32.4‰) arctic surface water from 0 to 150 m, overlying warmer (0.5 to -1.2° C) and more saline (33.5 to 34.8‰) water of the Atlantic Layer which extends to below 800 m.

In the Arctic Ocean, perennial sea ice 2 to 3 m thick forms when the surface layer freezes and expells dense cold brine, which sinks to about 130 m forming a strong pycnocline between the arctic surface and atlantic water layers (Aagaard *et al.*, 1985). An average thickness of 20-50 cm new ice is added each year, but in most years this growth is balanced by ablation.

On Axel Heiberg shelf, most of the sea ice consists of multiyear floes about 2 m thick. Because of the large shelf depth, most of the ice that forms here does not have access to sediment, in contrast to ice in the shallow Beaufort Sea and Alaskan shelf (Reimnitz and Kempema, 1987) which entrains abundant fine sediment. Nonetheless, large, thick undeformed sea ice (sikussak-fast ice, 10 m thick) may form during long (about 20 years) cold periods in Nansen Channel (Wadhams, 1986). In parts of the northern Ellesmere Island coast, sikussak continues to grow, forming floating ice shelves up to about 50 m thick (Hattersley-Smith *et al.*, 1955). Here, the ice shelves may contain large volumes of coarse detritus derived from the seabed in shallow water, from coastal talus slopes, or from glaciers that have advanced into the ice shelves (Lemmen *et al.*, 1989). Occasionally, the outer edges of the ice shelves calve to form ice islands that drift westward in the Beaufort Sea Gyre, transporting debris to the study area (Hattersley-Smith *et al.*, 1955). The north coast of Ellesmere Island is also the probable source of ice bergs and ice islands which transport coarse sand and gravel to the western arctic ocean basins (Clark and Hanson, 1983).

METHODS

The present study is based primarily on examination of 6 piston and 32 gravity cores recovered in water depths 140 to 300 m (Fig. 2). Continuous 12 kHz and 3.5 kHz echosounder profiles were obtained in conjunction with coring and they provide a subsidiary data base for regional lithofacies correlation (Mudie *et al.*, 1985, 1986; Van Wagoner *et al.*, 1989).

The sediments are classified into facies (Hein *et al.*, 1990), following the rationale of De Raaf *et al.* (1965). Physical properties measurements include: bulk density, pressure (p) wave velocity and attenuation (Mayer and Marsters, 1989), and magnetic susceptibility, using the method of Andrews and Jennings (1987), uncorrected for grain size. Foraminifera, palynomorphs and organic carbon were systematically examined in four cores (see methods in Aksu and Mudie, 1985b; Macko *et al.*, 1986a, 1986b). Quantitative analysis of foraminifera and other microfossils were done in surface samples and representative facies from the various cores (Schroeder *et al.*, 1990). Radiocarbon dating by accelerator mass spectrometer (AMS) provided ages for 7 samples of mollusc and formaninifera shells.

DESCRIPTIONS AND INTERPRETATIONS OF LITHOFACIES

Lithofacies are defined in Hein *et al.* (1990) and are summarized in Table I. Micropaleontological and palynological characteristics are given in Tables I and II. Representative x-radiographic photographs (Fig. 3) and a generalized lithologic chart (Fig. 4) illustrate the essential descriptive features of the facies.

FACIES A: SOFT PEBBLY-SANDY MUD (surface to 0.1 m depth)

Very poor sorting, absence of stratification, high frequency of gravel and coarser clasts, and the occurrence of drop-stone structures (Fig. 3) (Table I) indicate that this facies was derived from the fallout of ice-rafted debris. Facies A has a high biogenic content (10,897 forams/10 cm^3) and a high benthic species diversity (48-53) (Macko *et al.*, 1986b), both of which may reflect well-ventilated bottom water and high nutrient content associated with brines released during ice formation (Aagaard *et al.*, 1985). In general, calcareous microfossils are well preserved except for thin ferromanganous coatings. The most common palynomorphs recovered from Facies A include, Neogene-Quaternary pollen and spores (most commonly: *Polytrichum*-type moss, *Gramineae*, and *Pinus strobus*-type) and Quaternary dinoflagellate cysts and algal spores (most commonly: *Brigantedinium simplex* and *Diplopsalis* spp.) (Table II). Although neither physical sedimentary structures nor trace fossils are preserved in Facies A, this may be a consequence of very high bioturbation rates, coupled with slow sedimentation rates. Forams from the middle of Facies A in core 18 dated 7150 ± 80 BP (TO 594).

The most likely sources of coarse clastics in Facies A are localized drifts of shelf ice or ice bergs, laden with debris, as presently found within the Milne Ice Shelf, northernmost Ellesmere Island (Jeffries, 1986a, 1986b; Jeffries and Serson, 1986). Coarse ice-rafted debris may also come from periodic breakup of sikussak-fast ice from Nansen Sound. This source accounts for the common occurrence of Paleozoic limestone and dolostone clasts, and the presence of maroon pyroclastic rock (Hein *et al.*, 1990), which resembles volcaniclastic rock east of Cape Hubbard (Fig. 2) (Fortier *et al.*, 1963).

FACIES B: MOTTLED SILTY/CLAYEY MUD (0.1-0.25 m depth)

This sediment is fine-grained with less sand than Facies A. Granules are rare and pebbles were not observed (Fig. 3, Table I). In cores, Facies B shows well-defined round, tubular, or oval mottles, interpreted as biogenic sedimentary structures (*cf.* Ekdale *et al.*, 1984). Identifiable trace fossils include *Thalassinoides, Rhizocorallium, Terebellina, Chondrites, Planolites*, and *Skolithos* (Table I).

No palynomorphs were recovered from samples of this facies and foraminifera are absent in Facies B in Nansen Channel. This absence may be due to local anaerobic conditions (which favoured dissolution of any tests) and the likelihood of the occurrence of landfast sea ice in Nansen Sound. In other locations on the Axel Heiberg shelf, some samples contain both planktic and benthic foraminifera, and the benthic fauna is similar to that in Facies A, dominated by the deep Atlantic water indicator, *Cassidulina laevigata*. There is, however, a marked reduction of numbers (6485 total forams/10 cm^3), benthic species diversity (24-29), and planktic/benthic ratio (0.6) in Facies B compared with Facies A (Macko *et al.*, 1986b). Tests have a milky color and there is an absence of thin shelled foraminifers and aragonite shells, providing additional evidence of early dissolution.

FACIES C: WISPY LAMINATED/MOTTLED MUD (0.3-0.8 m depth)

Some primary laminations are preserved in Facies C (Fig. 3). Laminations are discontinuous and consist of sharp-based, normally-graded, laminated or rippled, sand-silt lenses, which fine upward into mottled clayey mud. No trace fossils were identified.

Compared with Facies A and B, Facies C displays a marked reduction of total forams (1530/10 cm^3), benthic species diversity (20), and planktic/benthic ratio (0.39) (Macko *et al.*, 1986b). Unlike Facies B, the calcareous benthic

TABLE I

Summary of facies description

Facies	Munsell Soil Colour	Colour Description	Lithology	Bed Thickness Range (mean)	Sedimentary Structures	Sorting	Micropaleontology/Palynology	Consistency
A	10 YR 4/2 to 10 YR 5/4	Greyish yellow to yellowish brown	Pebbles 1-2 cm dispersed in silty-sandy mud	10-22 (5) cm	None. Angular to subangular clasts.	poor to very poor	Calcareous microfossils ~ 30% of coarse fraction; abundant planktic and benthic foraminifera, common ostracods, pteropods, bryozoans and molluscs. Abundant siliceous sponge spicules. Rare radiolaria and diatoms (late spring blooms of diatoms).	very soft
B	10 YR 5/1 with 10 YR 4/1 mottles	Greyish with brown mottles	Sandy-silty mud or clayey mud	1-55 (20) cm	Burrowed, trace fossils: *Thalassinoides, Rhizocorallium Terebellina; Chondrites Planolites* and composite burrows. Rare *Skolithos* in sandy beds.	poor to mod.	Calcareous and arenaceous foraminifera common (Sverdrup Channel) or absent (Nansen Channel). Where present, planktic foraminifera << benthic numbers.	soft
C	10 YR 5/3 to 10 YR 5/2 in 10 YR 3/1	Brownish to olive grey lenses in medium to dark grey	Lenses of silt/sand in clayey mud	laminae: 0.2 (0.03-4) cm; stacked units up to 65 cm	Wispy, discontinuous lamination of sharp-based silt-sand lenses, which normally grade into clayey mud. Tops of lenses are commonly bioturbated. Lenses are laterally discontinuous; thinner laminae appear as streaks.	mod. to good	Common calcareous foraminiferal including both planktic and deep water benthic species. High organic content (>1%), but mainly reworked Tertiary organic debris and terrestrial palynomorphs.	upsection: soft to compact; in deeper cores, firm
D	Upsection: 10 YR 5/2 to 5 Y 4/2 Downsection: 5 Y 3/1 to 5 Y 5/2	Upsection: medium to dark brown alternating with yellow or light grey laminae. Downsection: dark olive grey or grey.	Sand-silt laminae alternate with sandy-silty mud/silty-mud	laminae: 0.2 (0.03-4)cm; stacked units up to 35 cm.	Continuous parallel-lamination, of sharp-based silt-sand which alternate or grade into sandy-silty-mud and silty-mud. Laminae are ungraded; normally graded; inversely graded; and inverse to normally graded.	mod. to good	Low numbers of calcareous planktic and benthic foraminifera, including a higher percentage of dextral-coiling *Neogloboquadrina pachyderma*.	upsection: soft to firm; in deeper cores, firm
E	5 Y 3/1 to 5 Y 5/2	Dark grey/olive grey-brown	pebbly-sandy (silty)-mud; rarely granule-cobble-mud	20 (3-45+) cm	None. Random chaotic or vertical pebble fabrics generally overlie or are interbedded at the base with convoluted/folded or brecciated sandy-silty mud. Vague diffuse stratification less common, angular, sub-angular and sub-rounded clasts.	very poor	Barren or contains rare planktic and benthic foraminifera, sponge spicules or mollusc fragments.	firm to very firm
F	7.5 YR 3/2 to 7.5 YR 4/4 5 YR 2/2; 5 YR 4/1; 5 YR 3/3; 5 YR 3/2	Reddish-brown/ochre	pebbly-sandy mud/ silty mud; sand & sand-silt interbeds. Boulders dredged (up to 50 cm dredged)	5-15 cm	Structureless to vaguely stratified, rare cross-beds in finer interbeds	poor to mod.	Abundant pollen, spores and terrigenous organic debris of ?Paleogene age. No marine microfossils. Petrified wood fragments.	very firm to semi-indurated
G	5 Y 3/1	Dark grey-black	pebbly-sandy mud	5-8 cm	None. Clasts are sub-angular, sub-rounded and rounded.	poor	Barren	very firm to semi-indurated
H	10 YR 4/2 or 5 Y 3/1 with 10 YR 5/2	Brown or dark grey with rare yellow-brown interbeds	silty-mud rarely sandy or pebbly	<5 to 30 cm	Mainly structureless; less commonly faint sand or silt laminae (0.2-0.5 cm thick). Isolated granule or pebble clasts scattered in the mud.	mod. to very poor	Planktic and calcareous benthic foraminifera rare or absent; soft coal fragments, bored; pollen and spores common.	firm

TABLE II

List of palynomorphs from representative core samples, showing dominant and/or age diagnostic species which characterise late Quaternary (Facies A) and older sediments on Axel Heiberg shelf (Facies E, H, F) (a = abundant; c = common; r = rare)

Lithofacies	A	E	H	F
Pollen and Spores:				
Neogene-Quaternary				
Alnus viridus	5 %	5%	22%	–
Ambrosia	5	–	–	–
Betula > 20 microns	–	10	4	–
Betula nana-type	5	15	3	–
Carya sp.	–	–	5	–
Cyperaceae	–	–	3	–
Ericales	–	5	5	–
Gramineae	14	–	–	–
Quercus	–	5	–	–
Pinaceae indet.	–	–	11	–
Pinus strobus-type	14	20	–	–
Picea banksii	–	20	–	–
Picea mariana	5	–	–	–
Tilia	–	–	3	–
Tsuga viridifluminipites	–	5	–	–
Osmunda fern	–	–	11	–
Polypodium fern	–	–	7	–
Polytrichum-type moss	52	–	–	–
Sphagnum moss	–	–	11	–
Cretaceous-Paleogene				
Alnipollenites	r	r	–	10
Appendicosisporites	–	–	–	r
Caryapollenites viridifluminipites	–	–	–	5
Cicatricosisporites	r	r	r	–
Normapolles	–	r	r	c
Parvisaccites	–	r	–	5
Pesavis tagluensis	–	–	–	r
Pityosporites labdacus	–	c	–	–
Stereisporites spp.	–	–	–	15

Lithofacies	A	E	H	F
Tiliapollenites sp.	–	–	–	5
Triprojectacites spp.	–	–	c	c
Wodehousia sp.	–	–	–	5
Dinoflagellate Cysts and Algal Spores:				
Quaternary				
Brigantedinium simplex	30	–	–	–
Diplopsalis spp.	13	–	–	–
Halodinium minor	3	–	–	–
Leiosphaeridia sp. A	6	–	–	–
Polykrikos hartmanii	3	–	–	–
Neogene-Pleistocene				
Lingulodinium sp.	–	13	–	–
Operculodinium centrocarpum	–	38	–	–
Melitosphaeridium choanophorum	–	10	–	–
Spiniferites elongatus	–	13	–	–
Systematophora ancyrea	–	5	–	–
Late Cretaceous-Paleogene				
Deflandrea sp. A	–	–	–	r
Oligosphaeridium complex	–	–	–	r
Palambages forma A	–	–	–	5
?Spongodinium sp.	–	–	–	c
Paleozoic				
Baltisphaeridium cf. *B. crinitum*	c	–	–	–
?Baltisphaeridium sp.	–	–	c	–
Veryhachium sp.	r	–	–	–
Foraminiferal Linings	a	c	–	–

foraminifera are well preserved and are dominated by the deep-water (at least 200 m) Atlantic species, *Cassidulina laevigata, Epistominella arctica* and *Stetsonia horvathi*. No palynomorphs were recovered from samples of this facies (Table II). The lower numbers, reduced diversity and low planktic/benthic ratios may reflect reduced plankton productivity as a result of higher clastic sediment input. Facies C is interpreted as indicating predominantly intermediate energy conditions during the deposition of clayey and silty muds by suspension fallout, with intermittent intervals of rapid erosion and deposition by fine-grained, low-density turbidity currents or bottom currents. Facies C was dated as 9570 ± 90 y BP (TO 595, Table III).

FACIES D: LAMINATED SANDY-SILTY MUD (0.25-0.3 m and 0.6-1.4 m depth)

Primary laminations are well preserved (Fig. 3), implying that the sedimentation rate exceeded the bioturbation rate. Where bioturbation occurs, it reaches 'downsection' from a depositional disconformity, which indicates intervals of rapid deposition (or deposition under anoxic conditions) stopped burrowing activity, which resumed when environmental stressors were reduced (*cf.* Andrews and Jennings, 1987; Gilbert *et al.*, 1990). Detailed textural analysis of this facies suggests that most of the lamination arises from fine-grained turbidity currents, alternating with suspension fall-out (Hein *et al.*, 1990). The local occurrence of dropstone structures (Fig. 3) indicates that there was some detrital input from melting ice bergs during the time of deposition of Facies D.

Foraminiferal assemblages in Facies D are dominated by similar species in Facies C: *i.e. Cassidulina laevigata, Epistominella arctica, Stetsonia horvathi*, and a presence of *Oridorsalis umbonatus* and dextral-coiling *Neogloboquadrina pachyderma*. This assemblage indicates relatively warm, saline water. However, the environment was stressed (possibly due to high sedimentation rates) as indicated by low benthic species diversity (20-24), low total numbers (1642-1696 forams/10 cm^3), and the occurrence of many intervals

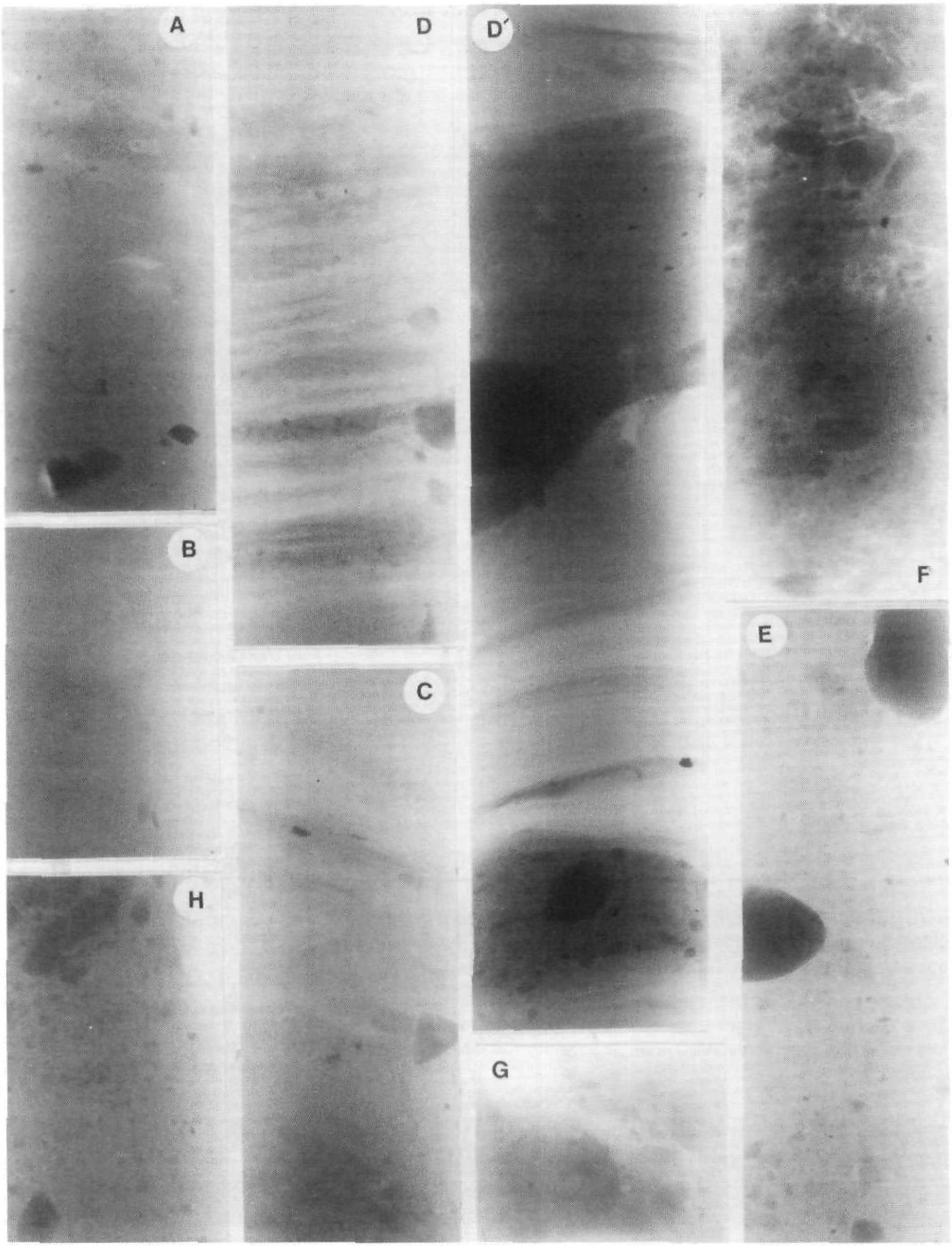

FIGURE 3. *Photoprints of X-radiographs, showing typical features of lithofacies.* A) pebbly sandy mud, core 18, 2-12 cm; B) mottled clayey mud, core 20, 3-9 cm; C) wispy-laminated silty mud with rare dropstones, core 18, 44-55 cm; D) laminated silty/sandy mud, core 18, 175-187 cm; D') laminated mud with disrupted bedding, core 53, 25-44 cm; E) gravelly mud core 22, 42-52 cm; F) semi-consolidated gravelly sand, core 52, 12-23 cm; G) semi-consolidated gravelly mud, core 58, 4-8 cm; H) stiff, grey sandy mud, core 18, 201-210 cm.

Radiographies montrant les principales caractéristiques des lithofaciès. A) boue sablo-caillouteuse, forage n° 18, 2-12 cm; B) boue tacheté argileuse, forage n° 20, 3-9 cm; C) boue silteuse en lamines mécheuses avec quelques cailloux de délestage, forage n° 18, 44-55 cm; D) boue silto-sableuse laminée, forage n° 18, 175-187 cm; D') boue laminée à litage interrompu, forage n° 53, 25-44 cm; E) boue graveleuse, forage n° 22, 42-52 cm; F) sable graveleux semi-consolidé, forage n° 52-12-23 cm; G) boue graveleuse semi-consolidée, forage n° 58, 4-8 cm; H) boue sableuse grise peu plastique, forage n° 18, 201-210 cm.

which are barren or contain only 2-4 planktic and benthic foraminifera. No palynomorphs were recovered from samples of this facies (Table II). The ratio of planktic/benthic species is moderate (0.5-1.0). The top of Facies D has been dated as 9950 ± 80 y BP (TO 1148) from foraminifera (Table III).

FACIES E: FIRM PEBBLY-SANDY MUD

The massive character, random distribution of coarse clasts within a finer-grained matrix (Fig. 3), low marine microfossil content, and virtual absence of stratification or grading (Table I) suggest that these deposits were emplaced very rapidly from highly concentrated, viscous, sediment-gravity flows and/or melt-out from debris-laden ice.

It is difficult to distinguish between poorly sorted debris flow deposits, till and ice-rafted deposits (Dreimanis, 1979), especially in unoriented, narrow (6 cm diameter) cores, and when debris flows include resedimented ice-rafted detritus. Thin Facies E deposits are characteristically lenticular, and occur on high slopes, within submarine channels, and grade downcurrent into turbidites. Locally thin Facies E units are associated with convoluted and/or slumped material (Hein *et al.*, 1990, Fig. 1). For these reasons, the thin Facies E most likely represents debris flow deposits. By contrast, thick Facies E (cores 63 and 102, Fig. 2) is less lenticular and confined to the shoreward, shallower shelf areas of the study area, contains foraminifera and sponge spicules, and most likely represents melt-out from debris-laden ice.

These interpretations are supported by the petrographic composition of the thick and thin Facies E units, in which significant differences occur in the percentage of sedimentary

Facies	Depth (cm)	Age BP	Micropaleontological notes	Sedimentation rate (cm ka^{-1})
A	4-6	1530	10,897 forams/cm^3	3.9
	6-8 8-10	1800 6810	ben. sp. div. 48-53 well ventilated bottom water	7.4 1.5
B	10-12	9420	6,485 forams/cm^3 ben. sp. div. 24-29 plank./ben. ratio 0.6; locally anaerobic stressed environment; low clastic input	0.8
C	33-40	9570	1,530 forams/cm^3 ben. sp. div. 20 plank./ben. ratio 0.4; high clastic input	113
D	89-91	9950	1,650 forams/cm^3 ben. sp. div. 20-24 plank./ben. ratio 0.5-1; some samples have very low numbers 2-4/sample; very high clastic input	134
E	80-170	no dates	rare planktic and benthic forams; Noegene-Quat. microfloral remains ; resedimented material	
H	75-200	no dates	marine microfossils rare or absent. Neogene pollen and spores; very high clastic input	
UNCONFORMITY				
F & G	0-25	no dates	no marine microfossils; petrified/chertified *Equisetum* stems L. Cret. and Paleogene pollen;	
			Terrestrial Bedrock	

FIGURE 4. Generalized lithologic chart showing the chronology of facies, Axel Heiberg shelf. See text and Table I for facies descriptions and interpretations. See Table III for details of ^{14}C ages.

Lithologie généralisée montrant la chronologie des faciès de la plate-forme de Heiberg. Voir le texte et le tableau I pour la description et l'interprétation des faciès. Voir le tableau III sur les âges au radiocarbone.

rock fragments (Hein *et al.*, 1990, Table II). Thin Facies E units (cores 6, 7, 54, and 112) average 23% sedimentary rock fragments (range: 3.5% to 59.4%). This contrasts with the thick Facies E units, which average 4% sedimentary rock fragments (range: 2.5% to 6%). Sandstone and siltstone fragments comprise the bulk of the sedimentary rock fraction of the thin Facies E unit (average 13%, range: 0.5 to 38.6%); whereas in the thick Facies E units sandstone and siltstone fragments are less common (average 0.8%, range: 0 to 1.8%). These petrographic variations reflect the erodability of the soft sedimentary rock fragments and the inferred type of sediment transport, with most of the soft fragments being destroyed during transport by ice (thick Facies E), and preservation of these soft rock fragments in debris flows (thin Facies E). Similar variations were noted in debris flow deposits and glacially-derived diamictons from Antarctica (Anderson, 1983).

Units of this facies are usually barren of microfossils or, alternatively, contain very rare planktic and benthic foraminifera, sponge spicules or mollusc fragments, including the sparse foraminifera *Cassidulina laevigata*, which only occurs in Arctic Ocean waters > 200 m water-depth (cores 63 and 102, Fig. 2). No datable foraminiferal or other shell material was recovered from this facies. The most common palynomorphs include: Neogene-Quaternary dinoflagellate cysts and algal spores (most commonly: *Operculodinium centrocarpum, Lingulodinium* sp., and *Spiniferites elongatus*) and Neogene-Quaternary pollen and spores (most commonly: *Picea banksii, Pinus strobus*-type, and *Betula nana*-type) (Table II).

The debris-flow interpretation for the thin Facies E units is further supported by the observed palynomorph assemblage (*cf.* core 54, Table II). This assemblage contains a mixture of Quaternary pollen and dinoflagellates and a large number of redeposited pollen and spores common in the lower Eureka Formation (Choi, 1983), such as triprojectates, Normapolles group grains, *Parvisaccites* and *Cicatricosisporites*. This redeposited flora contains many species that dominate Facies F in core 52 (Table II), which suggests that a local source for debris flows may have been the central shelf ridge on the Axel Heiberg shelf.

Similar deposits to Facies E can form by ice keel turbation (Vorren *et al.*, 1983). For several reasons, however, ice scour is an unlikely origin for Facies E, which occurs at present water depths of 145-283 m. Firstly, no keel gouges were observed in the 3.5 kHz records from the study area. Secondly, using data and studies of marine limits on northern Ellesmere Island (Bednarski, 1986; J. England, pers. comm., 1990), relative sea level on the Axel Heiberg Shelf was likely higher (10-30 m+) during the last glaciation. Thus, shelf water depths for the Facies E in the study area during the last glaciation probably ranged from *ca.* 155-293 m (minimum) to 175-313 m (maximum). The sparse foraminifera *Cassidulina laevigata* assemblage occurs in the most shallow water cores (63 and 102, at present water depths of 141 m and 145 m, Fig. 2), and indicates that for these cores the water depths exceeded 200 m in the past. Thirdly, field studies by England *et al.* (1978) indicate that the largest Late Wisconsinan glaciers calving off eastern Ellesmere Island (> 2.5 km elevation) were less than 150 m thick. Consequently, it is very unlikely that Facies E originated by ice-keel turbation by either floating ice bergs or by grounded glacial ice on the shelf in this study area.

PLIOCENE (?) FACIES H: COMPACT BLACK SILTY MUD (0.75 - 2 + m)

Facies H is composed of massive silty mud (Table I) (Fig. 3). The absence of biogenic traces suggest that either deposition was either rapid or that bottom water conditions precluded the activity of burrowing organisms (Hein *et al.*, 1990). Rare dropstone structures demonstrate some ice-rafting. This facies is interpreted as mainly hemipelagic in origin.

Marine microfossils are rare or absent (Table I); where present, their composition is variable, but it is essentially restricted to a few of the dominant deep water foraminifer species and rare sinistral-coiling *Niogloboquadrina pachyderma*. The palynomorph assemblage in Facies H is dominated by Neogene pollen and spore taxa (most commonly

TABLE III

Accelerator Mass Spectrometer (AMS) radiocarbon dates on molluscs or foraminifera, and estimated sedimentation rates for facies A to D

Lab.* No.	Core No. & Facies	Core Depth (cm)	Age (years) BP	∂ time (years)	Thickness** (cm)	Sedimentation Rate (cm ka^{-1})
TO 592 mollusc	94 (A)	4-6	1530 ± 60	1530	5	3.3
TO 593 mollusc	94 (A)	6-8	1800 ± 60	270	2	7.4
TO 594 foram.	18 (A)	5-6	7150 ± 80	top missing		–
TO 595 foram.	18 (C)	33-40	9570 ± 90	150	13.5	90
TO 1148 foram.	18 (D)	89-91	9950 ± 80	380	51	134
RIDDL 1223 foram.	37 (A)	8-10	6810 ± 110	6810	9	1.3
RIDDL 1224 foram.	37 (B)	10-12	9420 ± 110	2610	2	0.8

* TO = ISOTRACE Laboratory, University of Toronto.
RIDDL = radioisotope laboratory, Simon Fraser University. Core 37 is core 88-37 in 400 m of water west of Meighen Island (*cf.* Mosher *et al.*, 1988).
** In TO 595, the thickness is based on the depth of the contact between Facies B and C, and the assumption that this B unit has the same age (9420 BP) as Facies B in core 88-37.

Alnus viridus, Pinacea indent., *Osmunda* fern, and *Sphagnum* moss, Table II), with a small proportion of Paleozoic (?) acritarchs and Mesozoic triprojectate spores, indicating some input of redeposited organic sediment. The pollen assemblage suggests a late Pliocene age, possibly the Beaufort Formation.

The stratigraphic relationships between Facies D and H are not clear. Facies H is restricted to the lower parts of cores from Nansen and Sverdrup channels (cores 85-3 to 85-6; 6,7 and 18, Fig. 2). However, in core 54, there are two occurrences of Facies H: an upper unit interbedded with Facies D, and a lower unit towards the base of the core. The lower Facies H unit appears to be distinct from the overlying marine units. Magnetic susceptibility, bulk density, and longitudinal p-wave velocity data (Fig. 5) show that this unit is distinct from the overlying strata. As such, this lower Facies H probably represents an older stratigraphic unit which was not cored elsewhere, either because of the shallow depth to bedrock or because it was replaced by other facies elsewhere in more shallow-water sites.

PALEOGENE (?) FACIES: F, PEBBLY-SANDY MUD AND FACIES G, PEBBLY MUD (surface - 0.25 m depth)

These facies were interpreted by Hein *et al.* (1990) as possible Tertiary deposits, on the basis of their very firm to semi-indurated nature, distinctive coloration, and for Facies F the presence of petrified/chertified *Equisetum* stems (Table I). This interpretation is supported by newly acquired magnetic anomaly and magnetic susceptibility results, as well as more complete palynological results (Table II). It is important to discuss these relict facies because their occurrence on the shelf provided a secondary source for Facies E (see above discussion). Earlier petrologic studies indicate that Facies F, G and H were derived from the same source (Hein *et al.*, 1990).

Facies F and G are restricted to cores 52, 56, 57 and 58 (Fig. 2), all of which occur on the steep north slope of a ridge in the central inner shelf (Figs. 1 and 2). This ridge roughly corresponds to large positive magnetic anomalies (Forsyth *et al.*, 1988). A dredge sample from this ridge recovered diorite and quartzite boulders, cobble-sized sedimentary and volcanic rocks, and petrified wood. Palynomorphs are dominated by Late Cretaceous and Paleogene pollen and spores (most commonly *Alnipollenites* and *Stereisporites* spp., Table II). No marine microfossils were found. Thus, Facies F and G probably represent bedrock, belonging to the Paleogene terrestrial Eureka Sound Group (Miall, 1986). The Eureka Sound rocks are easily distinguished from the Neogene Beaufort Formation because the latter sediments are less consolidated, they contain only slightly altered wood and thin peats rather than coal and silicified wood (Hills and Ogilvie, 1970). Furthermore, pollen-spore assemblages of Beaufort age are dominated by modern tree genera, *e.g. Pinus, Picea, Betula*, and *Ericales*.

CHRONOLOGY OF FACIES AND SEDIMENTATION RATES

Details concerning the facies distribution among cores is given in Hein *et al.* (1990), and the chronology is summarized as follows (Fig. 4). Facies F and G are the oldest units, interpreted as terrestrial Paleogene Eureka Sound Group. They are unconformably overlain by the marine facies, of which the oldest, Facies H, recovered in cores from Nansen and Sverdrup channels (cores 85-3 to 85-6, and core 18,

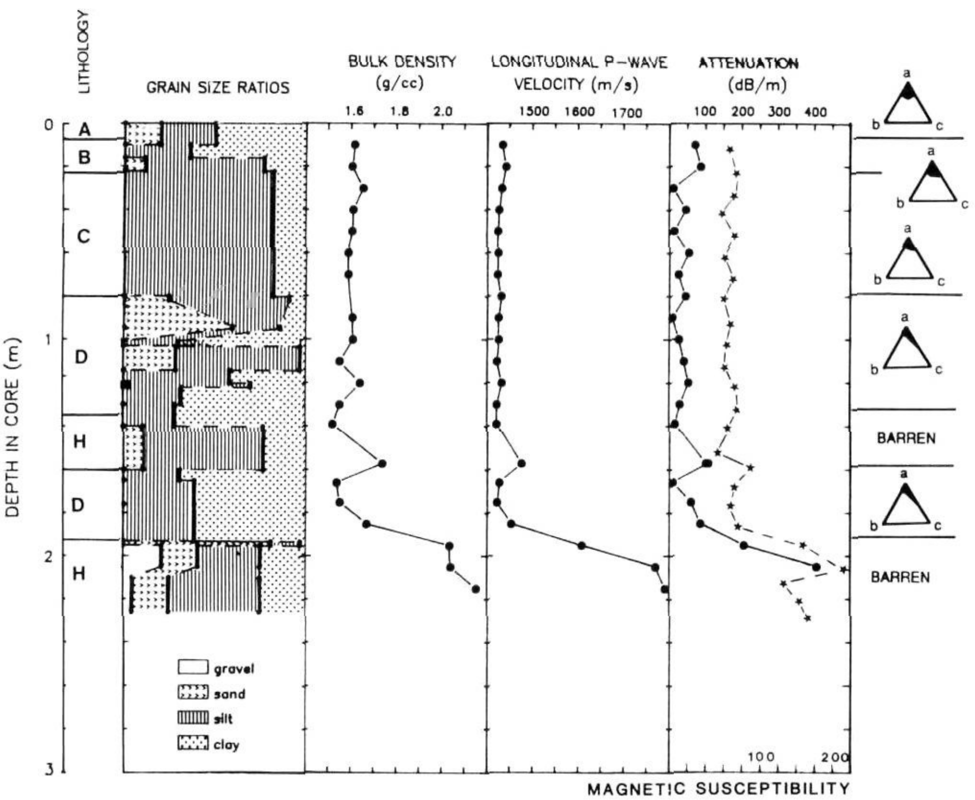

FIGURE 5. Lithology, physical properties, magnetic susceptibility (*–*–) in arbitrary units/gm, and ecological affinities (large triangles) of benthic foraminiferal assemblages in lithofacies of core 18. Attenuation is of sound at 500 kHz. See text for explanation of foraminiferal data, which uses the notation of Vorren *et al.* (1983) to indicate a: arctic, b: boreal, c: cosmopolitan.

Lithologie, propriétés physiques et susceptibilité magnétique (–*–) à l'intérieur d'unités/gm arbitraires et affinités écologiques (triangles) des assemblages benthiques de foraminifères dans les lithofaciès du forage n° 18. La colonne «atténuation» correspond au son à 500 hKz. Les données sur les foraminifères sont expliquées dans le texte selon les indications de Vorren* et al. *(1983): a) arctique; b) boréal; c) cosmopolitain.*

Fig. 2), is interpreted as Pliocene in age. There is no datable material from this unit. Facies E overlies Facies H in Sverdrup Channel (core 18, Fig. 2) and occurs at the base of all the longer cores from Sverdrup Channel and the Axel Heiberg shelf (cores 6,7,54,102 and 63, Fig. 2). No radiocarbon dates were obtained in Facies E, but palynomorphs suggest a Neogene — Quaternary age.

The marine facies dated as follows: top of Facies D, 9950 BP (TO 1148); Facies C, 9570 BP (TO 595); Facies B, 9420 BP (RIDDL 1224); and, Facies A from 1530 BP (TO 592) to 7150 BP (TO 594) (Table III, Fig. 4). In piston core 18, the older date for Facies A at shallow depths may be spurious because the top of the core may be missing. Core 94 (a trigger weight core) had intact, upright sponge mats, which were growing on top of Facies A. Thus, the top is intact for core 94, from which Facies A at 6 cm depth dated 1530 BP (TO 592). This contrasts with piston core 18, from which a 6 cm depth corresponds to 7150 BP (TO 594, Table III). Thus, the date at 5-6 cm depth in core 18 cannot be used to calculate the sedimentation rate nor the age of the top of Facies A. Core 88-37 (Mosher *et al.*, 1988 and Table III), a box core west of Meighen Island, also has an intact top. Thus, approximate sedimentation rates can be calculated for the marine facies A through D, assuming that there are no major hiatuses between the marine facies (Table III, Fig. 4).

FACIES A: SOFT PEBBLY-SANDY MUD

Facies A sedimentation rates vary from 3.3 to 7.4 cm ka^{-1} in core 94 (Table III) to 1.3 cm ka^{-1} in box core 88-37 (400 m of water, west of Meighen Island, Mosher *et al.*, 1988). In the Arctic Ocean, late Holocene ice-rafted sediments differ greatly in rate of deposition from about 1 m ka^{-1} on the Alaskan shelf (Barnes and Reimnitz, 1974) to 1 mm ka^{-1} on the Alpha Ridge (Mudie and Blasco, 1985). Otherwise these deposits resemble each other, distinguished only by differences in their sponge and benthic foraminiferal faunas, and by their gravel petrology.

This facies strongly resembles surficial sediments being deposited today beneath shorefast ice in the Canadian inter-island channels (MacLean and Vilks, 1986). Visual surveys and coring of the multiyear sea ice presently on the Canadian polar margin shows that most of the ice is clean or contains only thin (1 mm) layers of fine sand, silt and clay (Mudie *et al.*, 1985; Jeffries and Krouse, 1984). Suspended sediment in a trap towed 100 m above the seabed from August 1986 to August 1987 also indicates extremely low (< 2.5 g m^{-2} y^{-1}) influx of clastic and organic sediment (Hargrave *et al.*, 1989). Low ratios of living to total benthic foraminifera and common ferromanganese coatings on both living and dead foraminifera are additional evidence for very slow sedimentation at present. Thus, Facies A may be a product of ice rafting under conditions which favour some seasonal breakup, with ice-cover being perennial to the north and more seasonal to the south, as occurs today.

FACIES B: MOTTLED SILTY/CLAYEY MUD

Foraminifera from the top of Facies B collected in 400 m of water west of Meighen Island dated 9420 ± 110 BP (RIDDL 1224) (Mosher *et al.*, 1988 and Table III). Using this date along with a younger date of 6810 BP (RIDDL 1223) for the base of Facies A, yields a sedimentation rate of 0.8 cm ka^{-1} for Facies B. This is the lowest calculated sedimentation rate in the study area. The ^{14}C date of ~ 9400 BP coincides with a latter interval of stable glacial ice (England,

1990) and suggests that the top of Facies B is equivalent to the end of the last glaciation. Thus, Facies B may be a product of more severe sea ice-cover on the shelf, especially in Nansen Sound, such that breakup did not occur and there was no rafting of sediments which characterize Facies A. No driftwood has yet been found from this time-interval in the eastern circum-Arctic Ocean (J. England, pers. comm., 1990) also suggesting a stable sea-ice cover. The cold, dry conditions which gave rise to the more severe sea-ice cover until at least 9400 BP would also reduce coastal runoff, resulting in a reduction of plankton productivity and diversity of the area.

FACIES C: WISPY LAMINATED/MOTTLED MUD

Foraminifera from the middle of Facies C collected in core 18 dated 9570 ± 90 BP (TO 595) (Table III). Using this date along with a younger date of 9420 BP (RIDDL 1224) for Facies B, yields a minimum sedimentation rate of 90 cm ka^{-1} for Facies C. This is a moderately high sedimentation rate for the study area.

Periodic bottom currents or turbidity currents may produce wispy laminae. Velocities of more than 0.09 m s^{-1} are calculated for periodic shelf-break currents off Axel Heiberg shelf (Lewis and Perkin, 1987), and these are large enough to account for the wispy laminae (Hein *et al.*, 1990). Rapid deposition of sediment and intermittent traction currents would account for the low foraminiferal content, reduced diversity, and low planktic/benthic ratios.

FACIES D: LAMINATED SANDY-SILTY MUD

Foraminifera near the top of Facies D collected in core 18 dated 9950 ± 80 BP (TO 1148) (Table III). Using this date along with a younger date of 9570 BP (TO 595) for the middle of Facies C, yields a minimum sedimentation rate of 134 cm ka^{-1} for the basal Facies C and uppermost Facies D. This is the highest sedimentation rate calculated in the study area. This facies has previously been interpreted as fine-grained turbidites (Hein *et al.*, 1990).

Although there is no information available on turbidity current flows in the Arctic Ocean, sediment trap and current meter data obtained during ice-free periods in Itirbilung Fiord, Baffin Island, provide a modern analog for the origins of identical laminated facies (Syvitski and Hein, in press). Nine turbidity current events were documented in 50 days, each event lasting between 1 and 5 hours, with maximum current velocities of 0.36 m s^{-1} and sedimentation rates averaging 9 cm a^{-1} (Syvitski and Hein, in press). Although, sedimentation rates were not measured beyond the fjord-mouth (57 km offshore) detailed stratigraphic correlation of cores and acoustic records suggests that sedimentation rates due to turbidity current flows are at least two orders of magnitude lower beyond the fjord-mouth. This would correspond to sedimentation rate of 0.09 cm a^{-1} or 90 cm ka^{-1} for turbidity currents on the shelf. This estimate is well within the error of measurement for calculated rates (134 cm ka^{-1}) for the identical laminated facies on the Axel Heiberg shelf. Thus, on the Axel Heiberg shelf rapid deposition of sediment by turbidity currents would account for the observed low foraminiferal content, reduced diversity, and low planktic/benthic ratios of this facies.

SUMMARY OF FACIES SUCCESSION AND HISTORY OF DEPOSITION

The most simple paleogeographic model to account for the distribution of facies on the Axel Heiberg shelf is one in which there are two major controls: 1) the extent and distribution of sea ice and shelf ice; and 2) the relative discharge of sediment and water from glacial meltout and/or river runoff in coastal zones. The history of Late Quaternary glacial-marine sedimentation on the Axel Heiberg shelf can be summarized as follows, from oldest to youngest (Fig. 6).

1) *PHASE D.* The deposition of Facies D is interpreted to have occurred in a relatively open ocean setting. However, gravel was not deposited on the central shelf as it is today when ice-rafted detritus is frequently released. Facies D was deposited from fine-grained turbidity currents transporting material to the outer shelf. High sedimentation rates and turbidity current activity precluded the establishment of vigorous epi- and infaunal populations. Planktonic marine productivity was very low, but benthic faunas indicate the presence of deep warm Atlantic water. Foraminifera at the top of Facies D provide an earliest Holocene age of 9950 ± 80 BP, suggesting that this is a late glacial unit. However, the interpreted ice-free, open conditions for Facies D do not match the late glacial condition inferred from the land record (England, 1990) (see discussion below). The paleogeographic reconstructions from the land record suggest severe aridity, with lack of open water, very cold temperatures and extensive sea ice, with no entry of driftwood at the late glacial stage.

2) *PHASE C.* The deposition of Facies C is inferred to have been in an ice-covered setting, with fast ice in the nearshore/shoreline areas, and a continuous perennial sea ice cover or ice shelf. Coarse material was trapped in the nearshore zone and diminished current activity was widespread over the inner shelf. Fine sediment was transported to the shelf as suspension fallout and intermittent silty clay turbidity currents. Local resedimentation along bedrock ridges may have occurred because of oversteepening of material deposited on high slopes and/or due to seismic shock associated with fault movement (Hein *et al.*, 1990). Sedimentation rates were somewhat less than that for phase D, and were somewhat greater than bioturbation rates. Foraminifera indicate deep water (> 200 m) and lower plankton productivity than at present. A minimum age for Facies C is 9570 BP.

3) *PHASE B.* Facies B is inferred to have been deposited under a more continuous, extensive ice-cover and the supply of sediment to the shelf is greatly reduced. Sedimentation during this period is mainly hemipelagic settling of silt and clay from very dilute plumes of sediment and meltout of sea ice. Bottom current activity is reduced due to the greater sea ice cover. Sedimentation rates are relatively low and are exceeded by bioturbation rates. The *Cruziana* ichnofacies suggests sedimentation under conditions of low- to medium energy. Arenaceous foraminifera indicate intervals of lower relative sea level (< 200 m) and ponding of low salinity water

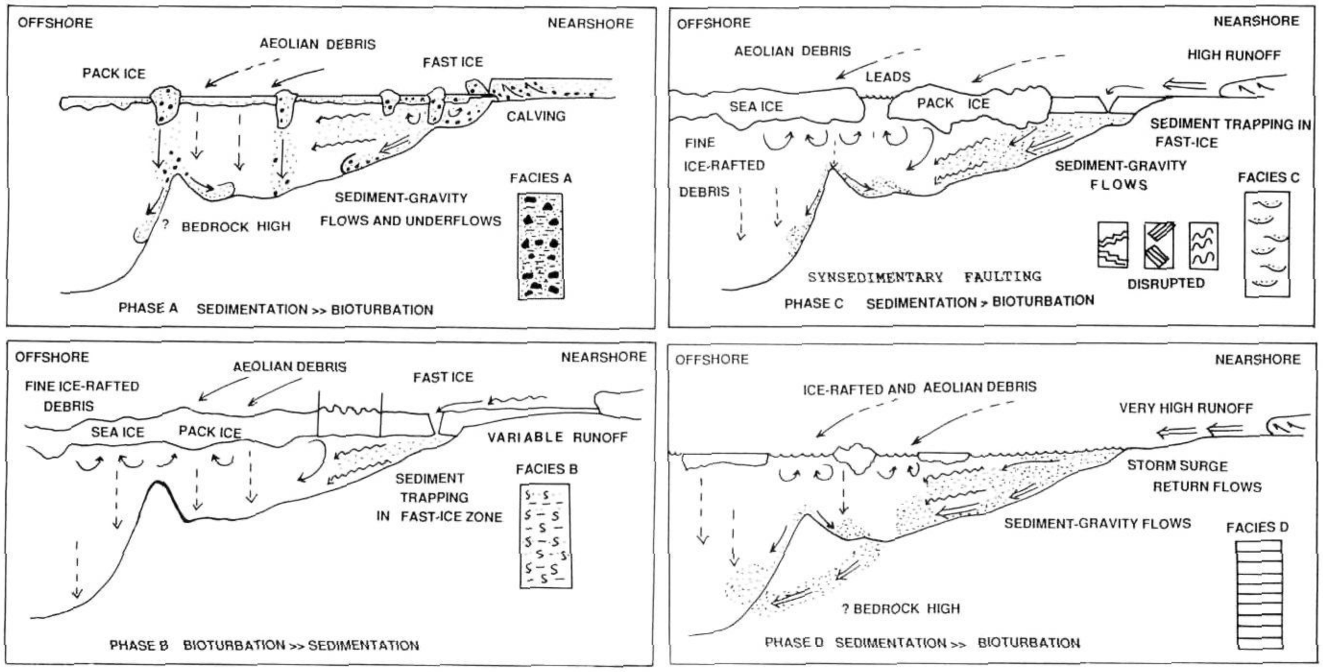

FIGURE 6. Conceptual paleogeographic model for glacial-marine sedimentation, Axel Heiberg shelf, Canadian Polar Continental Margin. Phases D to A correspond to late glacial age, Facies D to postglacial and recent Facies A; see text for details. Wavy lines at the top of the ice in Phase B indicate a possible sheared ice zone between shore fast ice and offshore sea ice.

Modélisation conceptuelle paléogéographique du processus de sédimentation glacio-marine, sur la plate-forme de Axel-Heiberg, à la marge polaire continentale. Les phases D à A correspondent au tardiglaciaire, le faciès D au postglaciaire et le faciès A à l'époque récente (voir le texte). La partie en dents de scie sur le sommet de la glace (phase B) montre une zone de cisaillement entre la glace de rive et la glace de mer.

in silled channels. On the Axel Heiberg shelf, Facies B is bracketed by an age of 7150 for Facies A and 9570 for the top of Facies C. The interval from *ca*. 7-9 ka in central Canadian Arctic islands appears to have been cold, with readvances of glaciers in some areas (Blake, 1970; Hodgson, 1985). The relatively fine texture and low foraminiferal content of Facies B supports this interpretation, and points to the presence of more extensive ice shelves or floating glacier lobes over the inner shelf.

4) *PHASE A*. Facies A is inferred to have been deposited in a relatively open ocean alternating with intervals of shelf ice and multiyear pack-ice as occurs today. The coarse-grained debris (medium sand to cobble) is ice-rafted material, supplied by meltout from grounded ice, from calving of shelf ice containing glacial debris, and calving of icebergs from Ellesmere Island glaciers. Finer-grained material (fine sand, silt and clay) is supplied by offshore winds and melting of sea ice. The base of this unit has a minimum age of 7150 BP, which broadly corresponds to regional deglaciation and rapid postglacial emergence in the Canadian high Arctic (England, 1990). The clastic and biogenic content of this facies closely resembles Holocene deposits seen elsewhere in the Arctic and circum-Arctic region. Historical records (Jeffries, 1986) indicate that the shelf ice was continuous along the northern Ellesmere Island coast during prolonged cold intervals (*e.g.* 1875 to 1906), and that massive wasting occurs during unusually warm intervals like the mid 1930's (Polunin, 1955). Considerably reduced summer sea ice has been reported for the Queen Elizabeth Islands between 6500 and 4500 BP (Blake, 1970; Stewart and England, 1983). This may have promoted increased rafting and sedimentation on the Axel Heiberg shelf during Phase A. Although deposition of coarse sediment in Facies A has probably been intermittent, it was likely uniformly higher during the initial retreat of glaciers following 7500 BP (Hodgson, 1985; England, 1990).

DISCUSSION

Sedimentation on the deep Axel Heiberg shelf, located in the coldest, driest part of the Arctic margin, differs from that on the shallow, seasonally ice-free Alaskan shelf or on the late-glacial Norwegian shelf, where grounded ice and ice keel turbation are major agents shaping the sediments. On the cold Canadian Polar Margin west of Ellesmere Island, local relief and climate combine to minimize the importance of ice scouring while the influx from annual runoff is constrained by the cold climate.

There is no clear evidence of grounded ice lobes on the Axel Heiberg shelf, and there is no *Elphidium clavatum* fauna that record meltwater events in many Arctic fiords and interisland channels. Overall, the combined lithostratigraphic, geotechnical and microfossil data from bank and trough cores off Axel Heiberg Island show an absence of diamictons attributable to any previous ice advance onto the shelf during the time period recorded by cores — post-9400 BP. Sediments in these cores directly overlie Paleogene terrestrial bedrock (Figs. 2,3 in Hein *et al.*, 1990) which indicates that the shelf was eroded prior to the deposition of the overlying glaciomarine deposits. The contact between the bedrock and the glaciomarine units is very sharp, and is interpreted as an unconformity. There is no lag above this unconformity. It is possible that the unconformity was eroded by glaciers which advanced and then retreated, leaving no depositional record in the study area. Alternatively, given the absence of diamicton attributable to ice advance, it was likely never deposited in the area. The absence of glacial-age diamicton is supported by the minimum Late Wisconsinan ice margin model of Dyke and Prest (1987), and is also compatible with Ellesmere Island ice core data (Koerner *et al.*, 1987). England (1990, p. 268) further states that the last glacial ice limit was south of the study area.

Facies D on the Axel Heiberg shelf was deposited by turbidity currents in relatively open ocean water for the time period at least 9950 BP. This interpreted ice-free, open ocean setting does not match the interpreted late glacial extensive sea ice interpretation at the same time-interval based on the land-record (England, 1990). This apparent discrepancy may be due to diachronous deglaciation and emergence patterns between the Axel Heiberg shelf and Ellesmere Island. England (1990, p. 268) states that deglaciation and emergence in the north coast fjords began about 10 ka, whereas ice retreat and emergence to the south began later, about 8 ka and increased at 6.2 ka. The high sedimentation rates associated with the deposition of Facies D probably reflect the deglacial event in the north coast fjords. An isostatic rebound curve for Expedition Fiord on western Axel Heiberg Island also shows a rapid fall from a marine limit beginning prior to 9 ka (Muller, 1963). Thus the sedimentation patterns associated with deglaciation appear to be diachronous across the Queen Elizabeth Islands, with deglaciation and emergence beginning in the northern coastal area perhaps 2 ka prior to deglaciation further to the south.

CONCLUSIONS

(1) Detailed sedimentological/micropaleontological analysis and radiocarbon age-dating shows that the shelf in this area experienced three dominant styles of sedimentation: Phase A, from the present to about 7000 BP, low sedimentation rate, with a high influx of coarse ice-rafted debris; Phase B, from > 7000 to about 9500 BP, very low sedimentation rate, with no influx of coarse ice-rafted debris; and Phases C and D, from about 9500 to > 9950 BP, very high sedimentation rate, with a low influx of coarse ice-rafted debris.

(2) A qualitative paleogeographic model shows that in the past intervals of more continuous ice cover, with a reduced influx of ice-rafted debris, alternated with more open water conditions, and a high sediment input from meltwater and/or floating icebergs.

(3) This shelf experienced post-Paleogene emergence and erosion. Prior to 9950 BP the shelf was inundated and has remained considerably below wave base, at many times water depths exceeded 200 m. Present water depths may be the shallowest on this shelf since post-Paleogene inundation.

(4) No diamictons interpreted as glacial till were cored on the Axel Heiberg shelf, indicating that this part of the Canadian Polar Margin was not covered by grounded ice during the last glaciation.

(5) A very high sedimentation period occurred on the Axel Heiberg shelf approximately 9950 BP. This anomalously high sedimentation event was orders of magnitude higher than that recorded for any other time period on the shelf. Sedimentation is inferred to have been by turbidity currents, which flowed into a generally ice-free, deep shelf-margin. This high sedimentation period possibly marks meltwater discharge to the shelf from rapidly retreating glaciers south of the study area. At this time, the rapid deglaciation and emergence in this area greatly increased sediment and fluid discharge to the Axel Heiberg shelf, forming thick turbidite units.

(6) General time-stratigraphic correlations between the marine-based chronology established here on the Axel Heiberg shelf and the land-based chronology documented by other workers to the south suggests that deglaciation and emergence were diachronous across the Canadian Polar Margin, and that deglaciation commenced earlier along the northern coastal margin.

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REFERENCES

Aagaard, K., Swift, J. H. and Carmack, E. C., 1985. Thermohaline circulation in the Arctic Mediterannean Seas. Journal of Geophysical Research, 90: 4833-4846.

Aksu, A. E. and Mudie, P. J., 1985a. A 4 million-year Arctic Ocean magnetostratigraphy dated by palynology. Nature, 318: 280-283.

——— 1985b. Late Quaternary stratigraphy and paleoecology of northwest Labrador Sea. Marine Micropaleontology, 9: 537-557.

Anderson, J. B., 1983. Ancient glacial-marine deposits: their spatial and temporal distribution, p. 3-92. *In* B. F. Molnia, ed., Glacial-Marine Sedimentation. Plenum Press, New York.

Andrews, J. T. and Jennings, A. E., 1987. Influence of sediment source and type on the magnetic susceptibility of fiord and shelf deposits, Baffin Island and Baffin Bay, N.W.T. Canadian Journal of Earth Sciences, 24: 1386-1401.

Barnes, P. W. and Reimnitz, E., 1974. Sedimentary processes on Arctic shelves off the northern coast of Alaska, p. 439-476. *In* J. C.

Reed and J. E. Sater, eds., The Coast and Shelf of the Beaufort Sea. Arctic Institute of North America, Arlington.

Bednarski, J., 1986. Late Quaternary glacial and sea-level events, Clements Markham Inlet, northern Ellesmere Island, Arctic Canada. Canadian Journal of Earth Sciences, 23: 1343-1355.

Blake, W., Jr., 1970. Studies of glacial history in arctic Canada. I. Pumice, radiocarbon dates, and differential postglacial uplift in the eastern Queen Elizabeth Islands, arctic Canada. Canadian Journal of Earth Sciences, 7: 634-664.

Choi, D. K., 1983. Paleopalynology of the Upper Cretaceous-Paleogene Eureka Sound Formation of Ellesmere and Axel Heiberg Islands, Canadian Arctic Archipelago, Ph.D. thesis, Pennsylvania State University, 545 p.

Clark, D. L. and Hanson, A., 1983. Central Arctic ocean sediment texture: a key to ice transport mechanisms, p. 301-330. *In* B. F. Molnia, ed., Glacial-Marine Sedimentation, Plenum Press, New York.

Clark, D. L., Whitman, R. R., Morgan, K. A. and Mackey, S. D., 1980. Stratigraphy and glacial-marine sediments of the Amerasian Basin, central Arctic Ocean. Special Paper 181, Geological Society of America, 57 p.

DeRaaf, J. F. M., Reading, H. G. and Walker, R. G., 1965. Cyclic sedimentation in the Lower Westphalian of North Devon. Sedimentology, 4: 1-52.

Dreimanis, A., 1979. The problems of waterlain tills, p. 167-177 *In* Ch. Schluchter, ed., Moraines and Varves — Origin, Genesis and Classification. Proceedings INQUA Symposium on Genesis and Lithology of Quaternary Deposits, Zurich, A. A. Balkema, Rotterdam.

Dyke, A. S. and Prest, V. K., 1987. Late Wisconsinan and Holocene retreat of the Laurentide Ice Sheet. Géographie physique et Quaternaire, 41: 237-264.

Ekdale, A. A., Bromley, R. G. and Pemberton, S. G., 1984. Ichnology: Trace Fossils in Sedimentology and Stratigraphy. Short Course Notes 15, Society of Economic Paleontologists and Mineralogists, 317 p.

England, J., 1976a. Postglacial isobases and uplift curves from the Canadian and Greenland High Arctic. Arctic and Alpine Research: 8, 61-78.

——— 1976b. Late Quaternary glaciation of the eastern Queen Elizabeth Islands, N.W.T., Canada: Alternative models. Quaternary Research, 6: 185-202.

——— 1983. Isostatic adjustments in a full glacial sea. Canadian Journal of Earth Sciences, 20: 895-917.

——— 1987. Glaciation and evolution of the Canadian high arctic landscape. Geology, 15: 387-486.

——— 1990. The late Quaternary history of Greely Fiord and its tributaries, west-central Ellesmere Island. Canadian Journal of Earth Sciences, 27: 255-270.

Evans, D. J. A., 1988. Glacial geomorphology and late Quaternary history of Phillips Inlet and the Wooton Peninsula, northwest Ellesmere Island, Canada. Ph.D. thesis, University of Alberta, Edmonton, 281 p.

Forsyth, D. A., Broome, J., Embry, A. F. and Halpenny, J., 1988. Features of the Canadian Polar Margin. Journal of Geophysical Research, 93.

Fortier, Y. O., Blackadar, R. G., Glenister, B. F., Greiner, H. R., McLare, D. J., McMillan, N. J., Norris, A. W., Roots, E. F., Souther, J. G., Thorsteinsson, R. and Tozer, E. T., 1963. Geology of the north-central part of the Arctic Archipelago, Northwest Territories (Operation Franklin). Memoir 320, Geological Survey of Canada, 671 p.

Gilbert, R., Naldrett, D. L. and Horvath, V. V., 1990. Holocene sedimentary environment of Cambridge Fiord, Baffin Island, Northwest Territories. Canadian Journal of Earth Sciences: 27, 271-280.

Hare, F. K. and Thomas, M. K., 1979. Climate Canada. John Wiley, Toronto, 230 p.

Hargrave, B. T., von Bodungen, B., Conover, R. J., Fraser, A. J., Phillips, G. and Vass, W. P., 1989. Seasonal changes in sedimentation of particulate matter and lipid content of zooplankton collected by sediment trap in the Arctic Ocean off Axel Heiberg Island. Polar Biology, 10: 1-9.

Hattersley-Smith, G., 1955. Northern Ellesmere Island, 1953 and 1954. Arctic, 8: 3-36.

Hein, F. J., van Wagoner, N. A. and Mudie, P. J., 1990. Sedimentary facies and processes of deposition: Ice Island cores, Axel Heiberg shelf, Canadian polar continental margin. Marine Geology, 93: 243-265.

Hills, L. V. and Ogilvie, R. T., 1970. *Picea banksii* n. sp., Beaufort Formation (Tertiary), northwestern Banks Island, Arctic Canada. Canadian Journal of Botany, 48: 457-464.

Hodgson, D. A., 1985. The last glaciation of west-central Ellesmere Island, Arctic Archipelago, Canada. Canadian Journal of Earth Sciences, 22: 347-368.

——— in press. Quaternary geology of the Queen Elizabeth Islands. *In* The Geology of North America. K-1, Chapter 19, Geological Society of America.

Horn, D. R., 1987. Recent marine sediments and submarine topography, Sverdrup Islands, Canadian Arctic Archipelago. Ph.D. thesis, University of Texas, 362 p.

Howard, J. D., 1978. Sedimentology and trace fossils, p. 13-47. *In* P. B. Basan, ed., Trace Fossil Concepts. Short Course Notes 5, Society of Economic Paleontologists and Mineralogists.

Jeffries, M. O., 1986a. Ice Island calvings and ice shelf changes, Milne Ice Shelf and Ayles Ice Shelf, Ellesmere Island, N.W.T. Arctic, 39: 15-19.

——— 1986b. Glaciers and the morphology and structure of Milne ice shelf, Ellesmere Island, N.W.T., Canada. Arctic and Alpine Research, 18: 397-405.

Jeffries, M. O. and Serson, H. V., 1986. Survey and mapping of Recent ice shelf changes and landfast sea ice growth along the north coast of Ellesmere Island, N.W.T., Canada. Annals of Glaciology, 8: 96-100.

Koerner, R. M., Fisher, D. A. and Paterson, W. S. B., 1987. Wisconsinan and pre-Wisconsinan ice thickness on Ellesmere Island, Canada: Inferences from ice cores. Canadian Journal of Earth Sciences, 24: 296-301.

Lemmen, D. S., 1988. The glacial history of Marvin Peninsula, northern Ellesmere Island, and Ward Hunt Island, High Arctic Canada. Ph.D. thesis, University of Alberta, Edmonton, 176 p.

——— 1989. The last glaciation of Marvin Peninsula, northern Ellesmere Island, High Arctic, Canada. Canadian Journal of Earth Sciences, 26: 2578-2590.

Macko, S. A., Segall, M. P. and Pereira, C. P. G., 1986a. Geochemical and mineralogical studies of seabed samples from Byam

Martin Channel and Desbarats Strait areas in the Arctic Archipelago. Open File 1315, Geological Survey of Canada, 52 p.

Macko, S. A., Aksu, A. E. and Mudie, P. J., 1986b. Paleoclimatic history of the Nansen Sound area, Arctic Ocean. Geological Society of America, Program with Abstracts, 99: 678.

MacLean, B. and Vilks, G., 1986. Marine geological program in the Byam Martin Channel — Lougheed Island region, District of Franklin. Geological Survey of Canada, Paper 86-1A: 769-774.

MacLean, B., Sonnichsen, G., Vilks, G., Powell, R., Moran, K., Jennings, A., Hodgson, D. and Deonarine, B., in press. Marine geological and geotechnical investigations in Wellington, Byam Martin, Austin and adjacent channels, Canadian Arctic Archipelago. Report, Geological Survey of Canada.

Mayer, L. A. and Marsters, J., 1989. Measurements of geophysical properties of Arctic sediment cores. Canadian Department of *Supply and Services Report for Contract No.* W7708-7-9408/01-SB, Department of Oceanography, Dalhousie University, 50 p.

Melling, H., Lake, R. A., Topham, D. R. and Fissel, D. B., 1986. Oceanic thermal structure in the western Canadian Arctic. Continental Shelf Research, 3: 233-258.

Miall, A. D., 1986. The Eureka Sound Group (Upper Cretaceous-Oligocene), Canadian Arctic Islands. Bulletin of Canadian Petroleum Geology, 34: 240-270.

Mosher, D. C., Mudie, P. J. and Sonnichsen, G. V., 1988. ISIS field report 1988: Ice island sampling and investigation of sediments. Geological Survey of Canada, Bedford Institute of Oceanography, Open File Report 2043, 42 p.

Mudie, P. J. and Blasco, S. M., 1985. Lithostratigraphy of CESAR cores. Geological Survey of Canada, Paper 84-22: 59-100.

Mudie, P. J., Mosher, D. C., van Wagoner, N. A., Aksu, A. E. and Macko, S. A., 1985. ISIS field report: Ice island sampling and investigation of sediments. Geological Survey of Canada, Open File Report 1333, 46 p.

Mudie, P. J., Dabros, M. J. and Redden, A., 1986. Ice island sampling and investigation of sediments field report 1986. Geological Survey of Canada, Open File Report,43 p.

Muller, F., 1963. Radiocarbon dates and notes on the climatic and morphological history: Axel Heiberg Island Research Reports. McGill University, Montréal, 241 p.

Naugler, F. P., Silverberg, N. and Creager, J. S., 1974. Recent sediments of the East Siberian Sea, p. 191-210. *In* Y. Herman., ed., Marine Geology and Oceanography of the Arctic Seas, Springer-Verlag, New York.

Pelletier, B. R., 1966. Development of submarine physiography in the Canadian Arctic and its relation to crustal movements. Special Publication 9, Royal Society of Canada: 77-101.

Polunin, N., 1955, Attempted dendrochronological dating of Ice Island T-3. Science, 122: 1184-1186.

Reimnitz, E. and Kempema, E. W., 1987. Field observations of slush ice generated during freeze-up in Arctic coastal waters. Marine Geology, 77: 219-231.

Schroeder, C. J., Mudie, P. J., Cole, F. E. and Medioli, F. S., 1990. Late Holocene benthic foraminifera beneath perennial sea ice on an Arctic continental shelf. Marine Geology, 90.

Stewart, T. G. and England, J., 1983. Holocene sea-ice variations and paleoenvironmental change, northernmost Ellesmere Island, N.W.T., Canada. Arctic and Alpine Research, 15: 1-17.

Syvitski, J. P. M. and Hein, F. J., 1991. Sedimentology of an arctic basin: Itirbilung Fiord, Baffin Island, Canada. Geological Survey of Canada, Paper 91-11, 67 p.

Thorsteinsson, R. and Tozer, E. T., 1968. Geology of the Arctic Archipelago, p. 548-590. *In* R. J. W. Douglas, ed., Geology and Economic Minerals of Canada. Economic Geology Report 1, Geological Survey of Canada.

Van Wagoner, N. A., Mudie, P. J. and Cole, F. E., 1989. Siliceous sponge communities, biological zonation and Recent sea level change on the Arctic margin. Canadian Journal of Earth Science, 26: 2341-2355.

Vorren, T. O., Hald, M., Edvardsen, M. and Lind-Hansen, O.-W., 1983. Glacigenic sediments and sedimentary environments on continental shelves: general principles with a case study from the Norwegian shelf, p. 61-73. *In* J. Ehlers, ed., Glacial Deposits in Northwest Europe. Balkema, Rotterdam.